BHAKRA DAM MISHAP
REPORT OF THE ENQUIRY COMMITTEE
VOL 1

REPORT

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REPORT OF THE ENQUIRY COMMITTEE.

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13. Shri N.K.Arora - Sub-Divisional Officer, Reinforcement.

3. Failure of works in the hoist chamber region and sequence of events before and after the mishap.

3.1 The Hoist Chamber.

The hoist chamber is a 30X42X55 feet high subterranean structure built inside the right abutment hill on the top of the right diversion tunnel located about 92 feet upstream of the axis of the dam (see drawing No.BDD.3085 - figure -1, showing the dam, diversion tunnel and the hoist chamber and drawing No.BDD-120 and BDD 1248 - figures 2 and 3 showing elevations).

Underneath the hoist chamber, the tunnel section has been divided into two parts by two conduits, each one of which has at the upstream end an emergency gate 12'-11½" by 25'-4¼" and 15 feet downstream of the emergency gate a regulating gate 9'-1" by 22'-9". The hoist and control mechanism for operating these gates are housed in the hoist chamber.

The gates were designed for a static head of 330 feet (inclusive of vacuum head) corresponding to a reservoir elevation of 1476, and the hoist chamber structure was designed accordingly.

Purpose of the hoist chamber.

The hoist chamber and the conduit structure with its regulating and emergency gates were designed to serve a dual function; firstly to store water in the reservoir during construction stage for early irrigation and regulate its releases for purposes of irrigation and power, and secondly to enable final closure of the right diversion tunnel, when the lower tier of the outlets in the dam became operative and could be utilised for regulating releases of water from the reservoir. Thereafter the hoist chamber, the conduits and the right diversion tunnel were to be finally plugged with concrete. This final closure was scheduled to be begun from early October, 1959, and completed during the succeeding months.

About half a million acre feet of stored water were thus made available for irrigation and power in 1958-59 and about one million acre feet in 1959-60.

Construction of the hoist chamber.

The hoist chamber was constructed at an approximate cost of Rs.43 lakhs. Construction of the hoist chamber was started during July, 1957, and completed by May, 1958. There were considerable difficulties in its construction. The access was through an 8'X7' adit connecting to the gallery system of the dam. After the chamber was excavated to elevation 1260, the roof arch was constructed in seven segments during the period 12th October to 11th November, 1957. On completion of the roof arch, further excavation of the hoist chamber was taken up. While the excavation along the downstream and left walls was completed up to elevation 1215, the upstream and right walls were excavated upto 1237 only so as to prevent rock slides. After pouring concrete from 1237.96 to 1259.17, further excavatinn below 1237 was taken up. The enclosed Fig.4 shows the sequence of construction of the walls in the hoist chamber. There was a good grouting programme carried out both for conslidation of rock and grouting of cont~~r~~act surfaces. The walls between elevation 1237.96 and elevation 1215.5 were constructed from bottom upwards as given in Fig.5. Some portions of the right side wall of the upstream were, however, concreted after the walls above elevation 1237.96 were completed. In such portions adequate arrangement for grouting and venting of the contact area was provided.

The work had to be done in a very restricted space, which presented special difficulties in concreting and installation of the gates and hoist mechanisms. It was also a race against time. The erection of gates and hoist mechanism was completed just in time for the rising reservoir on 25th June, 1958.

The gates fitted in the conduits under the hoist chamber were obtained from Messrs. Wagnner Biro of Austria. The gates were of the fixed wheel type and each weighed about 70 tons. The regulating gates were assembled in the hoist chamber after the niche frames had been fixed in floor concrete. The emergency gates were, however, assembled in the right diversion tunnel in front of the relevant gate grooves prior to fixing of the niche frames.

3.2. Operation of the gates in 1958.

On 3rd July, 1958, the left diversion tunnel was closed by dropping steel bulk head at the upstream portal of the tunnel. On the same day at 4 P.M. the water supplies started being regulated through the right tunnel by operation of the hoist chamber gates. All the gates were kept fully open. (See Fig.8 for the location of emergency and regulating gates and their numbering).

On closure of the left diversion tunnel on 3rd July, 1958, the water level began to rise from El.1199. By I P.M. on 8th July, the water rose to elevation 1311 and started flowing over the spillway for the first time. All the gates in the hoist chamber were fully open till the 10th July and on 11th, the regulating gate No.4 was closed fully to save the pump house located near downstream portal of the right diversion tunnel. The gate was opened again on the 12th July.

Two air supply pipes each 4 feet diameter with centre line at elevation 1194 have been provided above the conduits downstream of the regulating gates. These pipes draw air from the space above the water level in the 50 feet diameter diversion tunnel downstream and supply air to the regulating gate recesses, where negative pressures were indicated by model tests. With the rise of the tail water level in the diversion tunnel, to elevation 1189, the air supply to the regulating gate recesses starts getting interrupted because of the periodical surges and waves within the tunnel, which tend to seal the air supply through the tunnel. At this stage, the aeration through the air pipes becomes intermittent and it was observed that air with tremendous whistling sound was sucked through the drain pipes provided for drainage of the hoist chamber into the tunnel and consequently the spindles of the counterweights of the gates could be seen oscillating with a swing on either side of the original position by as much as 1¼". Under such conditions, the regulating gates had to be fully closed to stop vibrations and the harmful effect thereof.

On the 17th July, 1958, both the regulating gates were fully closed as due to rise of tail water to elevation of about 1189, the tunnel would get sealed and aeration stopped. Regulating gates were partly opened on 21st and 22nd July and fully opened on the 23rd July, when the water inflow reduced from 1.02 lakh cusecs to 0.64 lakh cusecs and the tail water level dropped to below elevation 1189. The reservoir level at the time was 1331.2.

On the 31st July at 11 A.M., both the regulating gates were fully closed as the tail water again rose above elevation 1189 and the discharge went up to 1.02 lakh cusecs.

In the year 1958, the maximum reservoir level attained was 1356 on 7th August. During August, 1958, the regulating gates were partly opened on 12th and 15th and fully opened on the 16th when the reservoir level came to 1331. On 24th, with the reservoir level at 1317.2, the gate openings were reduced and the reservoir built up again. On 5th September, the reservoir level was 1320.4 and the regulating gates were set to meet the indent of 20,000 cusecs with consequent rise in reservoir level. Withdrawals from stored supplies started from 13th October, 1958, and continued till 17th January, 1959. During this period regulating gates had to be operated in every shift to control releases as per indent placed from time to time. On 17th January, 1959, the regulating gates were fully opened and thereafter the free flow of the river passed through the right tunnel.

Thus it will be seen that during 1958, regulation of gates was made many times with reservoir level going up to 1356. No unusual phenomenon is said to have been observed, but it has been stated that oscillations of the counterweigh spindles for the gates were observed with a swing of 1¼" either way, when the downstream river level rose abov 1189. Judging from the heavy vibrations that were noticed with only 300 cusecs passing through the syphons (later installed in the hoist chamber) with a head of no more than 50 feet and the terrific vibrations noticed earlier with a discharge of about 9,000 cusecs entering the hoist chamber as a result of the mishap, it can be reasonably concluded that vibrations must have continued to occur to a greater or lesser extent throughout the period of partial operation of gates since July, 1958, to the date of mishap in August, 1959.

3.3. Operation of gates during 1959 up to the end of July.

From 2nd March to 24th March, 1959, regulating gates were again operated to increase the reservoir level by five feet to stop timber from passing under logboom. The gates were being adjusted so as to release the indent supplies or river flow whichever was less. On 6th May the reservoir level was 1263.50. Reservoir level fell to 1235.9 on 24th May and rose again to 1247.4 on 27th May. During the period 27th May to 2nd June, gates were partially closed to allow only 6000 cusecs discharge through the tunnel so as to maintain a low tail water gauge for removal of downstream coffer dam. Subsequently, the regulating gates were set to meet the indents up to 21,000 cusecs. Reservoir level rose to 1314.80 on 18th June. The gates were raised and lowered as required till 29th June when the gates were fully opened. The gates remained open till 6th August except for two days between 10th to 12th July when the gates were partially closed.

3.4 Operations in August, 1959.

The gates remained fully open till the morning of 6th August when the reservoir level was 1379.30

Then the gates were kept at partial opening, the opening varying from time to time till 21st August 2.45 P.M. except from 9th to 12th when the gates were fully closed. The reservoir level gradually went upto 1430.9 on 21st August. The river outlets in the dam were closed on 13th August to examine the steel liners and the required discharges were met with only from the operation of tunnel gates thereafter. On 13th August the reservoir level was 1406. The details of operation of the gates during this period are given in appendices III & X and graphically in fig.7.

The one important observation made during this period was knocking in gate No.3 on 17th and 18th and to avoid this knocking, this gate was raised a total of 2.6 feet increasing the gate opening from 13 feet to 15.6 feet and gate No.4 was closed an equal amount reducing opening from 14' to 11.5'. The reservoir level at the time was 1421.40. One of the officers described the sound as of something rolling on the gate sill. The officer thought "the noise was of rolling stones along the bed which had collected on the upstream side". This was reported to Mr.Gill, Director, Directorate of Inspection and Control, and there was an inspection by Mr.Gill on 19th at 8.0 a.m. The noise was still persisting and was evidently due to vibrations. Also two hair cracks were noticed. It was not known when these occurred but they came to notice when the floor was cleaned for inspection. These cracks were described as fine with sign of rust intrusion. Fig.8 shows the cracks. On 21st morning, the day of failure, leakage was noticed in the adit tunnel drain leading from the hoist chamber at a point 4'-6" inside the adit. A pin hole 1/8" was stated to be visible and the water was coming without any force. Also the base plate of the upstream column supporting the hoists of the gates had separated from the floor at one edge. This was at 9.30 A.M. On passing a thin wire between the clear space, it was found that 3/4ths of the base plate was fully resting on the floor and 1/4th was clear by about 1/16" maximum. Sketches of the observations were given to the Executive Engineer, Concrete Inspection Directorate, shortly after midday, who in turn informed the Director. The Director, Mr.Gill, and other officers came to the hoist chamber at about 2.20 P.M. Mr. Gill found that separation of the upstream columns from the floor had slightly increased and was of the order of 1/8". He also heard a clear metallic sound indicating some snapping of a steel member. He felt therefore that a structural failure had taken place. He ordered the closing of the emergency gates. At 2.45 P.M. emergency gates 1 and 2 were operated from fully open position to fully closed position but these gates could not be closed completely. There was still four feet opening. Then at 3.30 P.M. regulating gate No.3 was closed from 13 feet to fully closed position, while regulating gate No.4 was not fully closed and remained 1/4 feet open. At 4 P.M. attempts were made to close the emergency gates fully and the openings in both the gates were reduced from 4 feet to about 8". The reservoir level at the time was 1431. On examination Sarvshri Parshan Singh and Jagmohan Singh, Executive Engineers, Mechanical, could not find any defect in the mechanical or electrical systems. At 3.30 P.M. in consultation with Shri Katoch, Superintending Engineer, Concreting, Mr.Gill decided to erect an emergency barricade to prevent the flooding of the galleries in case of a break through the hoist chamber. At about 4 P.M. Mr.Gill declared the hoist chamber as well as galleries at EL.1225 and lower as unsafe area and gave orders to vacate these immediately. This was done and all keymen were informed on the phone. At 4.30 P.M. the hole in the adit tunnel had increased in size and water was coming out with more velocity as from a house tap. The separation between the upstream column and the had also increased to about 1/2". Shri M.R.Chopra, General Manager, agreed with the steps taken so far by Mr.Gill, except regarding the location of the barricade. Shri Chopra felt that the site selected by Shri Gill was too close to the hoist chamber and decided to put in two barricades - one in the cable gallery leading to the power-house just at the point where the slope began in the gallery and the other in 1225 gallery at a point where it opened out on the left training wall.

At 5.15 P.M., Mr.Gill ordered all the officers also to go away. Two persons were posted at the end of the adit tunnel to watch the flow conditions. Mr.Gill reported in all four metallic sounds. Mr.Gill left the hoist chamber at 5.30 P.M. At 6 P.M., the leakage through the initial pinpoint in the adit gallery assumed the shape of a fountain. The water of the fountain touched the roof of the adit gallery and the space under upstream columns became 2½" to 3". There was a great thunder in the hoist chamber and within two minutes there was a rush of water into various galleries and into powerhouse through 1225 galleries.

During the enquiry, it was suggested that Right Diversion Tunnel gates could have been closed and the Hoist Chamber permanently plugged as soon as the water level in the reservoir rose sufficiently to allow the irrigation and power requirements to be met by releases through El.1320 River outlets. In the River Diversion Scheme for summer of 1959, as approved by the Board of Consultants, **the Right** Diversion Tunnel gates were to be kept operative for as long a period as possible for avoiding the over-topping of the flanks Water studies, copy enclosed, indicated that water level in the Reservoir could be restricted to safe limits only if during the rising flood maximum water was released through both River Outlets and Right Diversion Tunnel conduits. It was hardly possible to bring the abutment blocks high enough by about 15th July, 1959, so if the Right Diversion Tunnel gates had been closed any time before the finish of the flood season, then for a composite wet year assumed in the design studies, dam could have been outflanked with disastrous consequences in the rising stage of the reservoir.

3.5. Sequence of events after the mishap.

At the time of the mishap, the total discharge through the hoist chamber, inclusive of leakage through the galleries and the flow through the right diversion tunnel, was estimated to be about 9,000 cusecs, with reservoir-level at elevation 1430.5.

The water entered the gallery system of the dam through the 7'X8' access adit connecting the hoist chamber and the gallery system. Out of the total of 9,000 cusecs, it was estimated that about half was flowing through this adit. From the galleries of the dam , the leakage water started flowing out through the penstock tunnel No.7 on the right, the right cable gallery in the right spillway training wall, the visitors' galleries at elevation 1225 and into the left power-house via the left cable gallery. The flow through the left visitors' gallery partly discharged into the spillway and partly on to penstock

No.1 from which later it entered the power-house through openings in its upstream wall. To start with, water level in the power-house rose to about elevation 1210+, thus submerging the units 1, 2 and 3. Fortunately for the power plant, one of the draft-tube bulkhead gates designed to prevent the entry of tail water into the power-house gave way almost immediately, bringing about drop of water level in the power-house to a few feet above the tail water-level.

Immediate steps were initiated to stop the water entering the power house. This was successfully achieved by the 25th October, 1959, through two openings blasted in the spillway side wall of the cable gallery and dropping a 40 ton bulk head gate downstream of the openings, followed by the construction of a concrete plug behind the gate. The flow from the visitors' gallery was later diverted into the spillway by putting a wall of heavy steel girders at the left edge of the wall.

Simultaneously, on the 14th October, 1959, work on choking of the right diversion tunnel at its upstream entrance was taken in hand. Work was later started on the access tunnel, leading into the hoist chamber from the elevation 1360 construction railway tunnel and on the access tunnel leading to the downstream end of the hoist chamber from the 1225 railway tunnel for the right power plant. (See Fig.6).

To observe the effect of choking operations at the entrance to the right diversion tunnel on the water-levels in the hoist chamber and the diversion tunnel upstream, two holes were drilled from the rock surface, one into the roof of the hoist chamber and the other in the right diversion tunnel 347 feet upstream of the hoist chamber (see Fig.6). During the course of observations of the water-levels in the hoist chamber, it was found that there was heavy surging of water accompanied by loud noise and terrific vibrations, as a result of which some of the drill rods, which were lowered into it for purposes of observations, got unscrewed and fell into the hoist chamber. These heavy vibrations were also observed when the excavation for the upper access tunnel approached within about 35 feet of the hoist chamber.

The break-through from the access tunnel into the top of the hoist chamber was effected at elevation 1262 on 21st December, 1959, when the water level, as indicated in the observation holes, had dropped to elevation about 1249 inside the chamber. There was tremendous suction of air from the access tunnel due to the surges of water in the hoist chamber. The heavy vibrations which persisted in the chamber even at this lowered water-level were proof of more or less heavy vibrations that must have continued to occur during the period of regulation with partial opening of the gates.

The visual inspection disclosed that the emergency gates had been bodily lifted up out of their grooves, got twisted and broken and scattered on the hoist-chamber floor. Thus the emergency gates, the hoisting mechanisms, and niche frames of the emergency gate-recesses had all been blown up. Parts of the niche frames of the down-stream gate-recesses were also found broken and blown down. The downstream slots of the regulating gates were found filled with debris of emergency gates, hoists, etc. The materials found in the slots of gates 3 and 4 are as follows:-

Gate 3- Slot (left)	Bottom section of both the emergency gates. 1½ Intermediate Sections. Bottom Section of the left regulating hoist cylinder.
Gate 4. Slot right	Middle slot section of the hoist cylinder. Top and intermediate section of one gate lying flat. Top and intermediate section of the gate resting on the regulating gate edgewise. Damaged small pieces of gate such as roller, skinplate and erection beams. Some material was carried by the water under the galleries of the dam. A damaged hoist beam and two damaged hoists of emergency gates were lying in 1187 gallery. One of the erection girders 12"X6"X34½ feet long and small pieces of niche frame and control cabinets were lying in 1225 inspection gallery (photos 7 and 8). Fig.9 shows the position where the pieces were found in the galleries.

4. The precise cause or causes of the failure.

During 1958, maximum reservoir elevation of 1356 was attained on 7th August. At the time, regulation gates were closed. As the aeration of the gates became intermittent, leading to heavy vibrations with swing of spindles of 1¼" either side, when the tail water level rose to 1189 which is the top level of the down stream conduit, the regulating gates had to remain closed till such time as the tail water level dropped below 1189 or the requirements of canal could be met from overflow through the low spillway blocks of the dam. The niche frames in the upstream slots were subjected in addition to vibration stresses to an uplift of 7.05 tons per foot run of niche frame corresponding to a head of (1356-1215) 141 feet on the cover plate. At this stage, nothing untoward is stated to have been observed.

In 1959, a year later, on 9th August, regulating gates were aga closed till 12th August to raise the reservoir level. The reservoir level rose from 1389.6 on 9th to 1404 on 12th August. A head of 189 feet was exerted on the plate, giving rise to an upward pressure of 9.45 tons per ft. run of the niche frames. It may be noted that due the positioning of the seal on the upstream face of the downstream g there would be no uplift pressure on the downstream niche frames in closed condition of the gates. The pressure to which the upstream niche frames in the emergency gate slots were subjected per foot ru the frames corresponding to different gate openings and heads on th upstream cover plates are given in Figs. 7 and 10.

For the first time, the project officers noticed some disturbin rolling sounds on 17th and 18th August, 1959, and discovered cracks the hoist chamber floor on the 19th. It was stated during enquiry the chamber floor which was covered with dust was specially cleane the 19th for inspection of Mr.Gill. The maximum static head to da on the niche frame came between 9th and 12th August, 1959, when the gates were closed. The gates were partially opened at 16 hours on 12th and fully opened at 16 hours on 13th. They remained fully op till 12 hours on 14th after which they were regulated with partia gate opening till the date of mishap. The uplift pressure per foo run of niche frame dropped to 6.2 tons at full gate opening on 13th and 14th and rose again steadily from 9.0

to 9.67 tons on the date of failure. On closing the gates on 21st August, this pressure rose from 9.67 to 10.65 tons (Fig.7).

The cracks in the floor which were first noticed on 18th by Shri R.S.Gill might have occurred any time between the 9th and 12th or between the 14th and 18th August, 1959, with uplifts between 9 and 9.67 tons per ft. run of the niche frames. This indicated a gradual separation of the top 43 inches of the hoist chamber floor between the emergency and the regulating gates, due to the bond between this and the lower concrete of the wall having weakened as a result of vibrations caused by flow through partial openings of the gates. These vibrations have not been specifically mentioned except at the time of high tail water in 1958 and on 17th and 18th August, 1959, when knocking was recorded. In view of the heavy turbulence noticed in the hoist chamber subsequent to the failure, as mentioned in para (4), vibrations of some magnitude must have been taking place all along at partial gate openings. Once the water gets in even in a small area between the two layers the high pressures indicated above would progressively lead to complete separation and eventual failure of the top slab.

The dates of pour of the various lifts in this concrete block are shown in Fig.5. The last but one pour was completed to 1211.90 on 20th April, 1958, and the last pour of 43 inches was completed by 5th May, 1958. The concrete was laid from a concrete pump, the concrete having a slump of 5½ inches. The concrete was of sufficient strength (see appendix VIII). The surfaces between the layers were green cut and cleaned with pressure water. This procedure was adopted in pouring the concrete from elevation 1186 upwards. In the lower lifts, the earlier placed surface was sand blasted and cleaned, but due to the confined space, series of different operations such as form work reinforcement, erection of gate structure going on concurrently, need for effective ventilation, and race for time, the officers in charge stated that wet sand blasting could not be done in the top lifts. It was stated that the testing of gates in the hoist chamber and conduits was finally completed on the very day that the coffer dam upstream of the tunnel entrance(which prevented water entering the tunnel due to rise in river) got overtopped. Also in the erection of niche frames, the middle block between the gates was used sothat many of the vertical bars of $\frac{3}{4}$" at 15" centres in two layers on each face which were shown going to nearly floor level had to be bent. At the time of the inspection nearly 60% of the bars were so bent and did not rise into the top layer. The balance of bars were found sheared at the concrete level of 1211.9. The construction engineers said that in cases where the bars had to be bent, theyprovided separate bars for the top lift, welding them with the bent bars as in fig 11. Inspection showed traces of welding which could not confirm whether lap welding to the required length was done or only spot welding was provided. All these bars were considered to be distribution bars and not the main reinforcement.

The specifications provided for wet sand blasting at construction lifts to secure monolithic structure. In view, however, of the conditions stated above, the method of green cutting and final clean up was adopted as an alternative. The design of niche frame as supplied by the manufacturers of the gates and as approved by the foreign specialists working in the Design Directorate, did not provide for any special anchorage, which could secure positive monolithic action of the entire concrete block between the gates.

Presumably, the design was based on the entire concrete acting as a monolithic mass. The top construction joint as provided in the field happened to be too close to the chamber floor level, viz. only 43" below the floor. This was stated to have become necessary on account of difficulties of erection of the special type of the niche frames supplied by the manufacturers, which further prevented the adequate anchorage by vertical bars. The design of cover plate supplied by the manufacturers was also not of usual type so that the heavy anchorage generally provided was not possible. These various factors did not favour the monolithic action of the entire concrete in the middle block. In the absence of any balancing superimposed weight, the uplift pressure pushed up the top so that the failure started with appearance of tensile cracks on the top. One of these cracks was connected with the drainage gutter in the adit tunnel. Increase of water flow through this crack was indicative of the progressive lifting of the top concrete. Just before failure there was jetting through the cracks in the adit tunnel.

* Columns supporting the hoists of the gates are shown in Fig.12 which also gives the detail of fixtures to the concrete floor. As the top layer separated and began to lift the middle block, the column, on the upstream side began to get separated. The upstream concrete near the wall and adjacent to the niche was not evidently lifted up due to weighing down of the wall. The column bolts got snapped which were evidently the sound that Mr.Gill heard. The separation of the column base from concrete gradually increased from 1/16" to as much as 2½ to 3" just before failure.

Also the concrete on the upstream side next to the wall was not torn to top of lift. The failure occurred on a slope as can

* It may be pointed out that the initial layout and design of the hoist chamber structure gates and hoisting equipment were prepared by the Design Directorate under the advice of Mr. B.M.Johnson, Director, Bhakra Dam Design, Mr. E.E.Gonzales and Mr. D.Maccragar of U.S.B.R. and Mr. H.N. Walker of UNTA and others, in 1953 and 1954. The bids for the equipment were called on the basis of these designs and the equipment manufactured by Messrs. Waagner Biro of Austria accordingly. Once the equipment had been manufactured and the structural outline decided, no structural changes could have been possible in the design of the hoist chamber. floor and the anchorage of the niche frames, and the design had to be based on the assumption adopted for the actual design as executed.

be seen from photographs 5 and 6. The last phase of the failure was sudden and was accompanied by a force which ejected the 80-ton emergency gates and hoists out of the slots.

The various factors indicate that there was a structural failure of the floor concrete in the top lift due to separation between layers and water getting in and also upward forces transmitted through niche frame not being balanced by the weight of the concrete.

5. To advise whether all precautionary steps should be taken were duly adopted or not prior to the failure.

The failure that occurred at the hoist chamber is of the rare type due to causes mentioned above. The specifications provided that concrete should be laid with wet sand blasting of already cast faces. Some vertical reinforcements were provided to take care of shrinkage, but not as reinforcement to secure positive bond. These two provisions would under normal conditions have secured the monolithic functioning of concrete, as in fact they did during the entire period from July, 1958 to the time the first crack occurred, if it were not for the vibration stresses which continued more or less throughout this period, with consequent element of fatigue. The actual field conditions and difficulties mentioned earlier, however, did not permit wet sand blasting to be done in all cases and particularly because of the requirements of erection of niche frames, a large number of vertical bars had to be cut and welded instead of being carried right up. Even so, the layers appeared to have remained in tact despite the vibrations and the uplift pressures up to nine tons or thereabout of the niche frame per linear foot.

The Committee was informed that there were originally two alternative schemes for regulating the supplies through the Right Diversion Tunnel. One was through a 300 ft. shaft from the top of the hill with access for equipment, materials and personnel for construction from the top of the shaft and the other through a hoist chamber with access from the dam galleries. Both these alternatives provided only regulating gates and no emergency gates. From considerations of economy (Rs.7 lakhs approximately difference in the two alternatives) convenience of construction and the time factor for completion of the job, it was decided to adopt the hoist chamber alternative. Later, in order to ensure fool-proof operation of the regulating gates, it was decided to provide an emergency gate in front of each regulating gate. With the provision of the four gates instead of two, the economics and convenience of and time factor for construction would weigh more heavily against the shaft alternative, particularly because two separate shafts would be needed instead of one. The shaft design would have been more fool proof but perhaps considering that it was a temporary structure required only for two seasons and the time factor for completing the job as per schedule, the Board of Consultants adhered to their earlier decision in favour of the hoist chamber structure. It is because of this lack of anticipation of this eventuality that the possibility of a break-through in the hoist chamber and flooding of the connecting galleries was also not envisaged and therefore precautionary fool-proof measures such as provision of gates in the adit and/or gallery system were not thought of and suggested.

According to the water studies carried out for the 1959 flood season, it was estimated that with the five spillways blocks at El.1440, the reservoir level in a composite wet year (theoretically the worst imaginable year) would not rise above El.1470, but that with a flood impinging on a reservoir elevation of about 1447 during September, when the reservoir is maintained high in the interest of storage for irrigation, would not rise above El.1476. These conditions were checked on models and confirmed by model tests. The side blocks of the spillway and the spillway training walls were accordingly provided for those conditions. The central spillway blocks were thus kept at El.1440 and the abutment blocks and training walls carried to El.1476. As indicated under para 3.1, the gates and hoist chamber structure were designed against these conditions i.e. for a reservoir elevation of 1476 and a static hea of 330 feet. The operation of the reservoir was, therefore, in keeping with the approved proposals.

The specifications for the gates provide for regulation with partial gate openings in the conduits under the hoist chamber for all heads up to the maximum designed head (reservoir El.1476). This was checked up by model experiments and also confirmed by the manufacturers. The partial gate operation resorted to in regulation during certain periods was, therefore, not in conflict with the design provisions; although it is felt that extensive use of partial gate openings for such large gates did probably result in vibrations, not originally reflected in the model tests, which are a contributory cause of failure not anticipated earlier.

During the month of August, 1959, if it were possible to keep the gates fully open, the damage to the hoist chamber due to uplift might not have occurred (see fig.7 read with fig.10). This, however, would not have been possible throughout the period, because at times with discharge above a certain limit (possibly over 80,000 cusecs) the tail water would rise higher than 1189, and the gates would have to be closed. The possibility of damage therefore, would still exist during periods of such closure.

It is evident that partial damage had already occurred by the 18th when hair cracks in the Chamber floor were noticed for the first time. In other words, some entry of water had already taken place between the two layers of concrete. Thereafter,the failure was inevitable, irrespective of whether the gates were fully open or fully closed. In the circumstances, therefore, it was perhaps better that the gates were closed, for two reasons - firstly it enabled control of reservoir to be maintained thereby permitting utilisation of about one m.a.ft of stored water for irrigation and power; and secondly making it possible to effect final closure of the right diversion tunnel through choking operations at its entrance, which made it possible to enter the hoist chamber for final plugging of the conduits and hoist chamber itself.

6. To set out lessons thatmay be learnt from the incident and in particular to advise whether any works or devices could have been provided, or should even now be provided, which could nimimise damage in the event of flooding of dam galleries.

The first and foremost lesson to be learnt from this mishap to the hoist chamber is that in structures subject to heavy uplift, this upward force should be counter-balanced wherever possible by a dead weight of concrete or steel of almost equivalent magnitude; for instance in the case of the hoist chamber, this could have been secured by carrying the central wall up to the required height, possibly up to the roof of the chamber, with suitable small openings for locating the hoist controls and access to either side.

The second lesson is that in structures subjected to high uplift pressures the utmost care must be taken to see that the relevant concrete structure acts as a monolith and the possibility of one layer separating from the other is completely eliminated. This can be secured by standard methods of cleaning the surface and securing maximum possible bond, and in addition by means of adequate steel reinforcement or other special anchoring methods.

The third lesson is that in case there is an inter-connection of galleries, break through in one of which can cause damage to the remaining gallery system or other connected works, provision should be made for installation of isolating gates which could be operated for closure from remote control. In this connection, mention may be made of what happened at the Hoover Dam in the U.S.A., where the foundation galleries got filled up from seepage flow. In the case of the Bhakra Dam galleries, the water from the Hoist Chamber rushed into these with velocities as high as 130 feet without causing the least damage to the concrete surfaces in these galleries. This is a tribute to the high quality of concrete placed in Bhakra Dam.

Precautionary measures in this respect have already been taken in the galleries connecting with those provided in the heel clay concrete plug. Three steel gates have been provided at critical locations which would automatically close as soon as water starts rising in the galleries, thus isolating the main dam gallery system from the heel clay gallery system. Similar protective measures should also be provided at other critical locations and project authorities may be advised to install them before the reservoir fills up to higher levels.

In all high head installation work with slide, fixed wheel and other types of gates, though model tests may indicate vibration-free operation at partial gate openings, it will be desirable, in the interests of safety, that such gates be worked fully closed or fully open.

7. Conclusions.

The Hoist Chamber mishap at the Bhakra Dam posed a most difficult engineering problem the like of which had not been encountered anywhere in the World. References to outside organisations, consultants and literature elicited little worthwhile enlightenment as to remedial measures and the chances of success thereof and high-lighted the extremely hazardous and uncertain nature of such measures. This extremely discouraging response created an atmosphere of grave anxiety as to successful repairs to damage and, therefore, the completion of the dam and the functioning of the power plant according to schedule. Despite the nerve racking experience, which they had to pass through during this crisis and the most adverse factors set forth above, the Bhakra Engineers accepted the challenge and are now well on the way to the successful choking of the conduits and the hoist chamber, and the final closing of the right diversion tunnel. This they have accomplished with the collaboration of our Army and Navy personnel who also worked round the clock in a spirit of dedication.

The Committee wishes to place on record its appreciation and admiration of the solid efforts and the achievements of the engineers of the Bhakra Dam Administration and of the Army Engineers.

(A.N.Khosla)
Chairman.

(Kanwar Sain)
Member.

(M.S.Thirmale Iyengar)
Member.

(A.C.Mitra)
Member.

New Delhi,
28th March,1960.

(K.L.Rao)
Member.

MEMBERS OF THE INQUIRY COMMITTEE STANDING ON THE DAMAGED FLOOR OF THE HOIST CHAMBER UNDER THE SYPHONS

Standing from Left to Right:

K.L.Rao Thirumalo Iyongar A.N.Khosla

A.C.Mitra Kanwar Sain

(9.2.60)

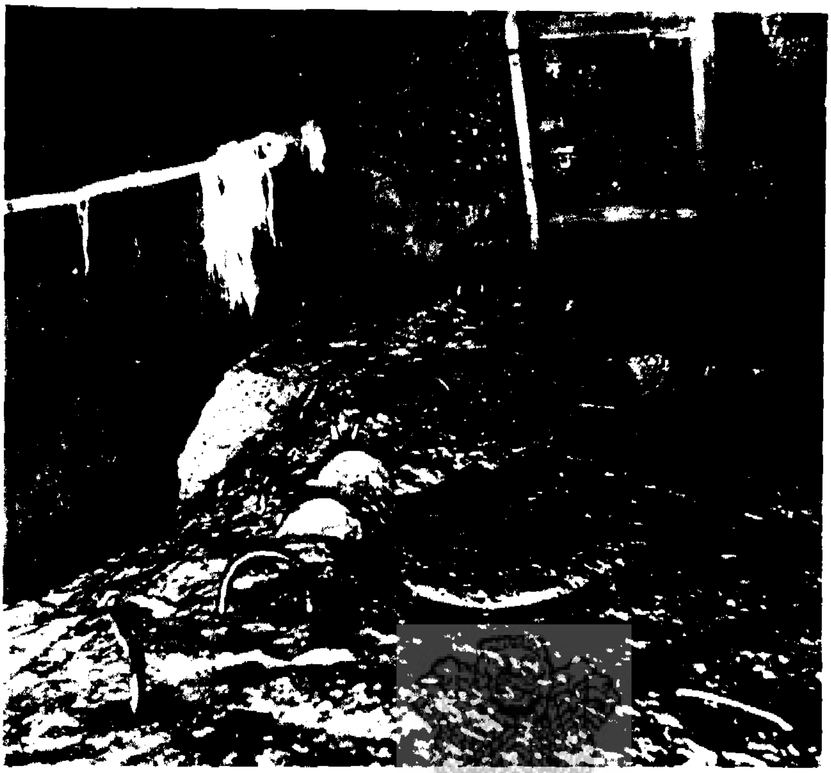
Photograph No. I.

DAMAGED FLOOR OF THE HOIST CHAMBER-RIGHT UPSTREAM VIEW-

Showing the top of lift 1211.9 vertical reinforcement bars hooked into the floor and two horizontal reinforcement bars. Syphon pipes for dewatering the Chamber are also seen in the right upstream gate slot.

(9.2.60)

Photograph No. 2.

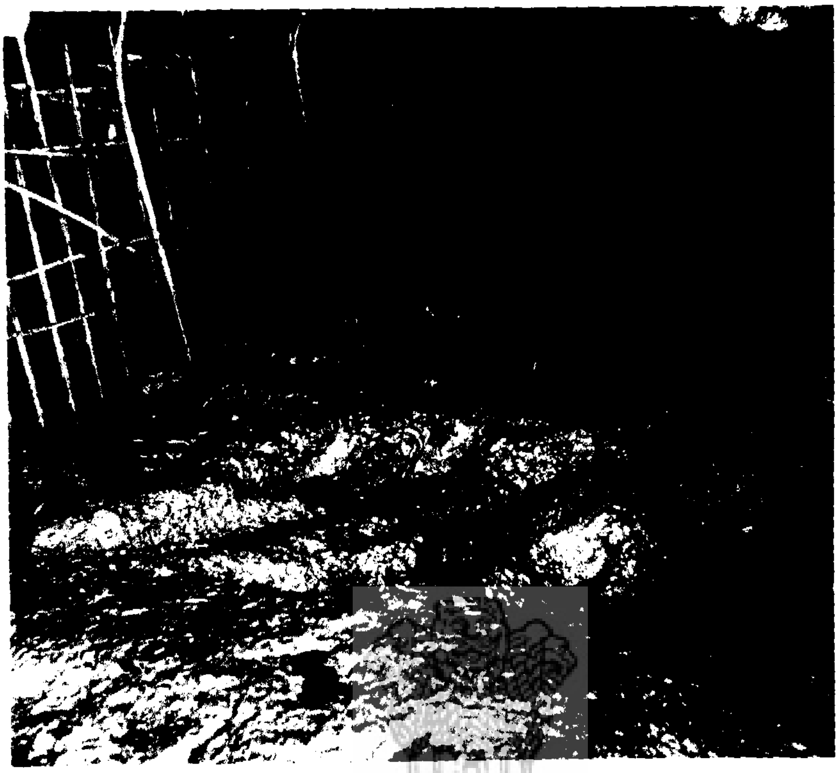


DAMAGED FLOOR OF THE HOIST CHAMBER- LEFT UPSTREAM VIEW

Shewing the top of lift 1211.9 vertical reinforcement bars hooked into the floor. Upstream left gate slot is also visible.

(9-2-60)

Photograph No. 3.



DAMAGED FLOOR OF THE HOIST CHAMBER-
RIGHT UPSTREAM AND DOWNSTREAM VIEW-

Showing the top of lift 1211.9 and reinforcement bars on both upstream and downstream sides. The mesh of reinforcement standing vertically on the left side is the protective railing erected after dewatering of the Hoist Chamber

(9-2-60)

Photograph No. 4.

RIGHT EMERGENCY GATE SLOT-
UPSTREAM AND SIDE VIEW-

Showing lift 1211.9 on the upstream and side walls and sheared anchors of Niche Frames.

(9-2-60)

Photograph No. 5.

LEFT EMERGENCY GATE SLOT-
UPSTREAM AND SIDE VIEW-

Showing lift 1211.9 on the upstream and side walls and sheared anchors of Niche Frames.

(9-2-60)

Photograph No. 6.

ERECTION BEAM OF THE HOIST CHAMBER FOUND BEND AND TWISTED IN 1225 GALLERY OF DAM

This beam 34½ feet long was carried by gushing waters from the Hoist chamber to this location via the 8'x7' Adit, 8'x12' Access Gallery 10½'x21' Hoist Shaft and 8'x9' Visitors Gallery.

(Refer (A) on Fig. 9)

(1-1-60)

Photograph No. 7.

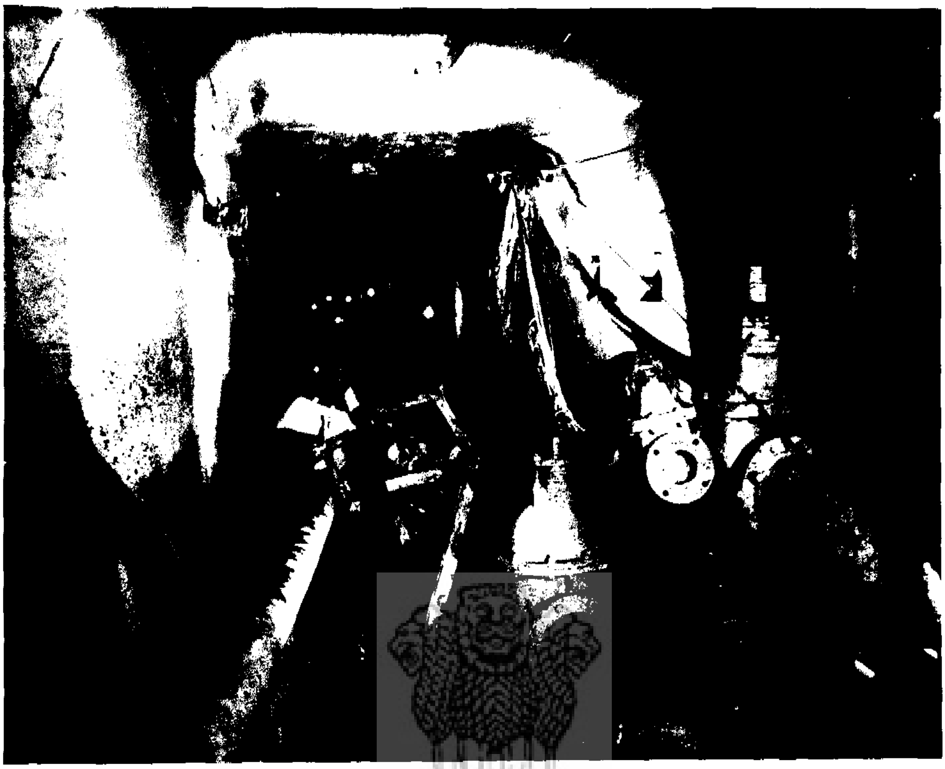
TWO OF THE HYDRAULIC HOISTS
STUCK UP IN THE 1187 GALLERY

These Hoists, weighing 8 tons each, were torn away from the gates and carried by water, via the 8'x7' adit into the 8'x12' Access Gallery.

(Refer (B) on Fig.9)

(21.1.60)

Photograph No. 8.



APIPE LINES IN SERVICE BEFORE THE ACCIDENT JUMBLED UP IN 1225 GALLERY.

(Refer C) on Fig. 9)

(1-1-60)

Photograph No. 9.

DOWNSTREAM VIEW OF HOIST CHAMBER CONDUITS OF THE RIGHT DIVERSION TUNNEL

Two 4-foot dia. air supply headers are seen above the two conduits. Leakage water is seen flowing through both the air headers and the conduits.

(Refer (D) on Fig. 3)

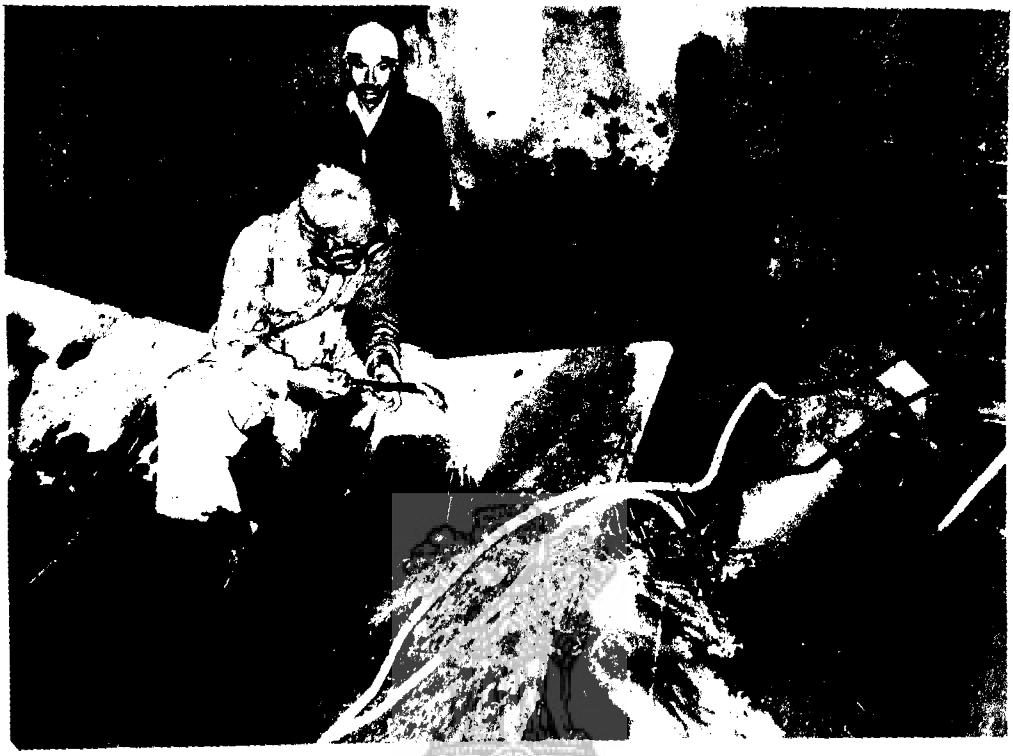
(31-12-59)

BROKEN GATES AND HOISTS ON THE HOIST CHAMBER FLOOR

As seen from the 1262 Access Tunnel blasted through the right side-wall of the Hoist Chamber. Pieces of Emergency Gates are partially blocking the left downstream slot. A piece of broken hoist is also visible.

(21-1-60)

Photograph No. 11.



SALVAGE OF DAMAGED GATES AND HOISTS ON THE HOIST CHAMBER FLOOR BY CUTTING INTO SMALL PIECES.

This hazardous work had to be done with leakage water swirling at high velocity all around.

(19-1-60)